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STATISTICAL EVALUATION OF CONE-PENETRATION-TEST DATA

by

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Foreword

The investigation reported herein was conducted by the U. S. Army Engineer Waterways Experiment Station (WES) in conjunction with projects sponsored by the Defense Atomic Support Agency (Nuclear Weapons Effects Research Subtask 13.010, Response of Buried Structure to Ground Shock) and the Office, Chief of Engineers, U. S. Army (Effect of Nuclear Weapons Project No. 1-T-0-22601-A-091-02, Development of Design Criteria for Foundations of Army Protective Structures). The tests were accomplished during July and August 1964.

The tests were conducted and this paper was prepared under the general supervision of Messrs. W. J. Turnbull and A. A. Maxwell, Chief and Assistant Chief, respectively, of the Soils Division, WES, and R. W. Cunny, Chief of the Soil Dynamics Branch (SDB), of the Soils Division, and under the direct supervision of Mr. J. G. Jackson, Jr., SDB. The test program was planned and executed by Mr. J. K. Poplin, SDB. Instrumentation and data recording were performed under the supervision of Mr. G. C. Downing of the Instrumentation Branch, Technical Services Division, WES. Messrs. H. T. Parsons and R. E. Manning and Pfc A. L. Brower, SDB, assisted in the testing and the reduction of data. The analysis and preparation of this paper were accomplished by Mr. Poplin.

Col. Alex G. Sutton, Jr., CE, and Col. John R. Oswalt, Jr., CE, were Directors of WES during the investigation and publication of this paper. Mr. J. B. Tiffany was Technical Director.

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Summary

In the study of foundation behavior, preparation of relatively large specimens of dry sand of uniform density and evaluation of these specimens in a nondestructive manner were required. Preliminary investigation indicated that the cone penetrometer could be used for this purpose, but an investigation was required before data from cone penetrations could be adequately interpreted.

An investigation was conducted using a typical laboratory specimen, and 121 penetrations were made with a 1/2-in.-diam 30-deg cone penetrometer. The penetrations were made at 6-in. spacings in various patterns to study the effect of penetration sequence, interaction, and boundaries. In addition, 25 density samples were taken from the specimen and a single plate-bearing test using a 6-in.-square plate was conducted.

The cone-penetration-resistance data and density data were subjected to standard statistical analysis. Differences in mean values from different zones in the specimen were compared to determine if real differences existed and were not the result of random scatter in data.

Density data indicated that the specimen was uniform within the capabilities of determination but that variations not accountable as random scatter in cone-penetration resistance existed between various points in the specimen. The effect of sequence and interaction appeared negligible at 6-in. grid spacing; boundary effects were somewhat inconclusive but probably insignificant. Disturbance produced by the plate-bearing test reduced cone-penetration resistance in a zone around the plate.

Cone-penetration resistance was found to be adequate for evaluating uniformity provided sufficient observations were made. Generally, about eight penetrations were required to yield a mean value which could be expected to be within 6 percent of the true mean value.

STATISTICAL EVALUATION OF CONE-PENETRATION-TEST DATA

Introduction

1. Prior to conducting model footing tests on large specimens of dry sand, it was necessary to develop procedures and techniques for controlled preparation of these specimens. This specimen-preparation requirement generated a need for a nondestructive test that could be used to determine a characteristic physical property of the specimen and also to assess the uniformity of the specimen construction. The cone penetrometer was selected as the device having the greatest potential for this test. The advantages of the cone penetrometer for this purpose are:

a. Cone-penetration resistance (CPR) is characteristic of the in-situ material and can be measured as a function of depth.

b. Measurements can be made simply and quickly.

c. Disturbance of the specimen due to the test is thought to be small.

A mechanically driven penetrometer was fabricated, and a capability for recording continuous CPR versus depth curves was developed in the Soil Dynamics Test Facility. Equipment details of the cone-penetration system are given in fig. 1.

2. Since CPR represents an indirect measurement of soil properties, correlation in terms of more basic properties, particularly unit weight, was considered desirable. For the purpose of correlating unit weight with CPR, cone-penetration tests were conducted in dry sand specimens contained in a sectional ring mold 19 in. in inside diameter and 18 in. deep. The results of the penetration tests in the ring mold were generally inconclusive, as CPR versus depth curves for seemingly identical conditions appeared to fluctuate considerably. A tendency toward increase in CPR with number of penetrations was noted. This buildup of CPR with number of penetrations was believed to be a boundary effect; for this reason, the ring mold was considered to be inadequate for further evaluation of CPR data.

3. On the basis of data collected in preliminary tests in the ring mold, the conclusion was drawn that CPR versus unit weight must be evaluated on a statistical basis. Therefore, a statistical pattern of evaluation tests was conducted in a large specimen of dry sand prepared in a mobile soil cart.

Objectives and Scope

Objectives

4. The objectives of the evaluation tests were:

a. To determine the statistical reliability of CPR data.

b. To investigate the boundary and interaction effects of penetration within the mobile-cart specimen.

c. To determine the influence of a static plate-bearing test on neighboring CPR tests.

d. To evaluate the relative uniformity of the prepared specimen.

Scope of tests

5. The following tests were considered essential to achieve the objectives listed above.

a. Cone-penetration tests. The cone-penetration tests were designed to obtain CPR data from several sequences of tests conducted in various grid patterns. The effects of penetration in a regular pattern, in interspaced patterns, and in proximity of the cart sidewall boundary were studied.

b. Plate-bearing test. A plate-bearing test was conducted to obtain load-displacement data for comparison of response of the plate to static loading with similar plates and specimens and to permit study of the influence of such tests on CPR by conducting neighboring penetration tests both before and after the plate-bearing test.

c. Density tests. Unit weight was determined at selected locations on the surface and within the specimen to evaluate local variations in unit weight and provide data for pointwise correlation of CPR with unit weight.

Tests and Test Procedures

6. The locations of the cone-penetration tests, plate-bearing test, and density tests are shown in fig. 2.

Penetration tests

7. A total of 121 cone-penetration tests were conducted in the specimen. The penetration tests were divided into series and further subdivided into test groups for analysis and comparison. The detailed layout and sequence of penetration for each series are shown in fig. 3.

a. Series A (regular grid pattern). This series consisted of a 5-by-5 matrix of 25 penetrations on a 6-in.-square grid. The location and sequence of penetrations are shown in fig. 3.

b. Series B (centrally diverging pattern). The 25 penetrations in this series were conducted in a sequence which expanded outward symmetrically about the center of the 5-by-5 matrix, as shown in fig. 3.

c. Series C (centrally converging pattern). The 25 penetrations in this 5-by-5 matrix were made in groups which interspaced the preceding groups of penetrations, as shown in fig. 3.

d. Series D (cross-section profile pattern). This series of 21 penetrations consisted of three test groups of seven penetrations at 6-in. spacings across the cart, as shown in fig. 3.

e. Series E (plate-bearing-test area). In a 5-by-5 matrix, 25 penetrations were conducted in the area of the plate-bearing test (see fig. 3). Of these, eight penetrations were conducted prior to the plate-bearing test, and the remaining 17 penetrations were conducted after the test.

Plate-bearing test

8. A static plate-bearing test using a 6-in.-square plate on the surface of the specimen was conducted using established procedures.* Load and settlement were recorded by an X-Y recorder, and a maximum settlement of 3 in. was accomplished.

* U. S. Army Engineer Waterways Experiment Station, CE, Technical Report No. 3-599, "Dynamic Bearing Capacity of Soils; Report 3, The Application of Similitude to Small-Scale Footing Tests," dated December 1964.

Density tests

9. Unit weight of the specimens was determined from 16 samples taken from the 0- to 2-in.-depth layer and nine samples from the 6- to 8-in.-depth layer with a box density sampler (see fig. 2). The samples from the surface were taken in a symmetrical array about the center of the penetration patterns of series A, B, C, and E; the samples from the lower layer were taken at randomly selected locations.

Specimen and Equipment

Sand specimen

10. A uniform fine sand, locally called Reid-Bedford Model Sand, was used to prepare the 20-in.-deep specimen in a mobile metal cart 11 ft 10 in. long and 3 ft 4 in. wide. The sand was placed in the cart using the single-orifice sand sprinkler* with a height of fall of 18 in. and a flow rate of 11 lb per min. The sand sprinkler and a partially prepared specimen in the cart are shown in fig. 4. The specimen was prepared with the cart positioned on platform scales, which permitted continuous monitoring of flow rate. The average unit weight of the specimen computed from the total weight of sand placed and the volume of the cart filled was 102.4 lb per cu ft or relative density of approximately 90 percent.

Penetrometer

11. The various components of the penetrometer system are shown in fig. 1. A 1/2-in.-diam, 30-deg cone with a 1/4-in.-diam shaft attached to a horizontal driving plate was driven in a vertical direction through screw gears by a variable-speed electric motor. The penetrometer assembly was mounted on a mobile support frame, which straddled the cart and moved laterally along a track on the frame. Zero reference depth was the point of burial of the cone, and penetrations were made to a depth slightly greater than 12 in.

Density sampler

12. The box density sampler used for unit-weight determination consisted essentially of a thin-walled, rectangular metal sleeve which is

* Memorandum for Chief, Nuclear Weapons Effects Division, subject "Static One-Dimensional Compression Tests on Reid-Bedford Model Sand," dated 4 August 1964, Appendix A.

pushed into the specimen. A prismatic volume of sand of approximate dimensions of 2 by 4 by 12 in. is removed from the sleeved enclosure with a special scoop gaged to remove material to 2 in. in depth.

Processing of Penetration Data

13. The recorded penetration resistance was scaled from the penetration-test curves at 1/2-in. intervals up to 12 in. deep and was entered on punch cards. Having defined CPR as the resistance load (pounds) divided by the base area of the cone (square inches), a digital computer program* was used to compute and tabulate the following data:

a. Average CPR for individual penetrations over selected intervals of depth: 0 to 3, 3 to 6, 6 to 9, 9 to 12, 0 to 6, 6 to 12, and 0 to 12 in.

b. Average CPR for series and test groups for the same intervals of depth as indicated in subparagraph 13a above.

c. Average CPR versus depth at 1/2-in. intervals of depth for series and test groups of penetrations.

d. The range of CPR comprising the average given in subparagraph 13c versus depth for the same grouping of data.

In addition to the data tabulated above, the data in subparagraphs 13c and 13d were punched on cards; the average, maximum and minimum CPR at each 1/2-in. interval of depth was plotted with an X-Y plotter.

Statistical Analysis of Data

Terminology and basic theory

14. Basic statistical symbols, terms, and definitions were used to evaluate the test results.**,*** The terms and definitions listed below are valid for small samples, i.e. $n < 30$:

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* Computer Program No. 41-G1-Z5025, Cone-Penetration-Resistance Averages.

** U. S. Army Engineer Waterways Experiment Station, CE, Miscellaneous Paper No. 2-250, "Basic Statistical Definitions and Procedures," dated January 1958.

*** Zelen, M., "Introductory Lectures on the Statistical Design of Experiments," U. S. Army Mathematics Research Center, University of Wisconsin, Madison, Wisconsin, dated February 1962.

Symbol	Definition or Derivation
x_i	Value of measurement of a single observation
n	Total number of observations in a set of data
$\bar{x}$	Arithmetical mean or average value, $\frac{1}{n}\sum_{i=1}^{n} x_i$
s	Estimated standard deviation of a single observation, $\sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}}$
s_m	Estimated standard deviation of the mean, $\frac{s}{\sqrt{n}}$
s_δ	Standard error of the difference of two means, $\sqrt{s_{m_1}^2 + s_{m_2}^2}$

15. The symbol s used above is the estimated or approximated value of σ, the true standard deviation of an infinite number of observations. In a plot of frequency of occurrence, f, versus value of measurement, x, the normal distribution curve is shown in fig. 5a. The peak value of f occurs at $\bar{x}$ and relative relation of σ or multiples of σ can be observed. From basic theory of probability, it can be shown that 68 percent of all observations lie within the range $\bar{x} \pm \sigma$, 95.5 percent lie in the range $\bar{x} \pm 2\sigma$, and 99.7 percent are in the range $\bar{x} \pm 3\sigma$. This means that any observation has approximately two chances out of three of being within the interval $\pm \sigma$ about the true mean and a one-in-three chance of falling outside the interval. Similarly, an observation has three chances in 1000 of falling outside the interval $\bar{x} \pm 3\sigma$.

16. The value of σ, or its estimated value s, is a measure of the dispersion of the data and, in effect, an index to the precision of the measurement technique. This is demonstrated by considering all the area under the normal distribution curve (fig. 5a) as unity or 100 percent. Then, the area between $\bar{x} \pm \sigma$ is 68 percent, between $\bar{x} \pm 2\sigma$ is 95.5 percent, and between $\bar{x} \pm 3\sigma$ is 99.7 percent of the total area. Hence, a small

where s_δ is the standard error as defined in paragraph 14 and t is the value for the combined degrees of freedom for the two sets. In this case, the degrees of freedom are $n_1 + n_2 - 2$. For the purpose of evaluating the cone-penetration data, a "go, no go" criterion was established for comparing mean values of groups of tests. If the value of $(\bar{x}_1 - \bar{x}_2)$* is less than or equal to the product ts_δ, the difference is said to be statistically insignificant. On the other hand if $(\bar{x}_1 - \bar{x}_2)$ is greater than ts_δ, the difference is said to be statistically significant. Statistical significance implies that a true difference may exist between the two sets (at least 95 percent of the time), while no conclusion can be drawn from differences that are statistically insignificant.

Analysis of penetration data

20. For the purpose of statistical comparative analysis, the average CPR over selected intervals of depth was found to yield more stable numbers than CPR at a particular depth. Contours of equal average CPR for 0 to 3 in. and 0 to 6 in. were constructed by linear interpolation between points on a 6-in. grid, as shown in fig. 6. Both figures tend to indicate that the average values of CPR did not change abruptly from point to point over the cart and the variations appeared to be random. Thus, evaluation of data on a statistical basis was feasible, and the 0- to 6-in. average CPR was selected for comparative analysis. Basic data are presented in table 1. A tabulation of the computed statistical quantities for series and test groups is shown in table 2. Differences in mean values between appropriate series and test groups are shown in table 3.

21. Series A. The 25 penetrations that constitute this series were made in consecutive order across the cart, then subdivided for purposes of analysis into test groups of square matrices starting at the lower left corner of the test pattern (fig. 3). Test A-1 consisted of a 2-by-2 matrix (four penetrations); test A-2 consisted of a 3-by-3 matrix (nine penetrations) with test A-1 as a submatrix. Test A-3 and series A continued the pattern, i.e. 4-by-4 (16 penetrations) and 5-by-5 matrices (25 penetrations), which included all penetrations in the previous tests as submatrices.

22. The effect of increasing the number of observations on the mean, standard deviation, and confidence intervals is shown in fig. 7. In this figure, individual penetration CPR, average test group CPR, statistical

* Since only the absolute value of the difference is of interest, the order of difference is immaterial.

value of σ produces a sharply peaked distribution curve, while a large value produces a low flat curve.

17. When it is not feasible to obtain sufficient data to determine a frequency distribution, special techniques are available for treatment of small samples.* When dealing with a limited number of observations, $\bar{x}$ is more significantly affected by a single observation than when working with data in which the frequency distribution can be better established. In the case of small samples, Student's theory can be used to establish confidence intervals, $\bar{x} \pm ts$, where t is Student's "t," a function of the confidence level and degrees of freedom.** Tabulated values of t may be found in statistical handbooks.*** The variation of t with degrees of freedom for various confidence levels is shown graphically in fig. 5b. For the purposes of evaluating the penetration-test data, a confidence level of 95 percent was arbitrarily selected for analysis, and future reference to the value of t implies the 95 percent confidence level value. On this basis, a conclusion drawn from the analysis has a 1 in 20 chance of being wrong.

18. Based on the foregoing discussion of statistical theory, the confidence interval (CI) for 95 percent confidence level (95 percent CI) for a single observation can be established. Any observation, x_i, can be expected to lie within the range $\bar{x} \pm ts$ for 19 chances out of 20. As previously stated, $\bar{x}$ computed from a limited number of observations may be biased by "bad" data from one observation and thereby caused to deviate from the true mean, $\bar{x}_{true}$. The 95 percent CI of the mean can be established and $\bar{x}_{true}$ can be expected to be within the range $\bar{x} \pm ts_m$ 19 times out of 20.

19. The mean values of sets of data can be compared statistically to determine if the difference in mean values is indicative of a true difference between the two sets or merely the result of purely random statistical variation. Consider two sets of data consisting of n_1 and n_2 observations with computed mean values, $\bar{x}_1$ and $\bar{x}_2$. A 95 percent CI for the difference of the mean can be established as $(\bar{x}_1 - \bar{x}_2) \pm ts_\delta$

* A small sample is generally regarded as a set of data consisting of less than 30 observations.

** In general, the degrees of freedom for a set of data is defined as: d.f. = n - 1.

*** Zelen, M., "Introductory Lectures on the Statistical Design of Experiments," U. S. Army Mathematics Research Center, University of Wisconsin, Madison, Wisconsin, dated February 1962, Table I.

where s_δ is the standard error as defined in paragraph 14 and t is the value for the combined degrees of freedom for the two sets. In this case, the degrees of freedom are $n_1 + n_2 - 2$. For the purpose of evaluating the cone-penetration data, a "go, no go" criterion was established for comparing mean values of groups of tests. If the value of $(\bar{x}_1 - \bar{x}_2)$* is less than or equal to the product ts_δ, the difference is said to be statistically insignificant. On the other hand if $(\bar{x}_1 - \bar{x}_2)$ is greater than ts_δ, the difference is said to be statistically significant. Statistical significance implies that a true difference may exist between the two sets (at least 95 percent of the time), while no conclusion can be drawn from differences that are statistically insignificant.

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interval about the mean of the standard deviation, 95 percent CI for a single observation, and 95 percent CI for the mean are shown. By increasing the number of penetrations from 4 to 25, average CPR changed by 1.0 psi. If the average value of 25 penetrations can be considered the true mean value, it is noted that the average of 4, 9, and 16 observations were within 3, 1, and 0.5 percent, respectively, of the mean of 25 observations. It is noted in table 2 that the value of s , the estimated standard deviation of a single observation, was nearly constant, consistent with the precision of the measurement technique, and was not affected by the number of observations. The 95 percent CI for a single observation and for the mean converge with increasing number of observations since "t" decreases with increasing degrees of freedom. As previously mentioned, the interval $\bar{x} \pm s$ should contain approximately two-thirds of all observations for a large number of observations. In fig. 7, this relation is shown to be generally true for the test data.

23. Series B. The penetration sequence used in this series completed the 6-in. grid by moving outward from the center in a symmetrical pattern. The average CPR for the five selected test groups in this series ranged from 35.7 to 39.4 psi, with an average of 38.0 psi for the series. From table 3 it can be observed that a difference of 0.4 psi between the average for this series and that for series A was not statistically significant. Test B-1 consisted of a single penetration at the center of the series pattern; test B-2 (four penetrations) and test B-3 (four penetrations) were conducted on an inner circumferential row. Test B-4 (four penetrations) and test B-5 (12 penetrations) were conducted on an outer row. Test B-2 was 2.9 psi greater than test B-3, a difference indicated to be statistically significant by a small margin (table 3). The difference of 0.1 psi between tests B-3 and B-4 was not statistically significant. When the 12 penetrations of tests B-2, B-3, and B-4 were combined for comparison with test B-5, the difference in average CPR of 1.1 psi was found to be statistically insignificant. Since the only difference for which statistical significance was indicated appears to be a borderline case, the effect of interaction from previous penetrations appears to be insignificant at 6-in. spacings.

24. Series C. This series consisted of test C-1 (one penetration) at the center, test C-2 (four penetrations) at the extreme corners of the outer circumferential row, test C-3 (four penetrations) at intermediate points in the outer row, test C-4 (four penetrations) at the corners of the inner circumferential row, test C-5 (four penetrations) at intermediate points in the inner row, and test C-6 (eight penetrations) to complete the grid pattern in the outer row. The average CPR ranged from 36.6 to 43.0 psi, with an average of 40.5 psi for the series. Comparison of the average value for this series with the average for series A and B indicated the differences in CPR were statistically significant. Comparison of the

results of test C-2 with test C-3 and test C-4 with test C-5 indicates that the differences in CPR of 1.1 and 2.0 psi, respectively, lack statistical significance. This agrees with the conclusion from the series B tests that interaction between penetrations appears to be insignificant at 6-in. spacings.

25. Series D. This series consisted of three tests of seven penetrations each across the cart. Average CPR values ranged from 35.9 to 39.3 psi for the three tests and the average for the series was 37.9 psi. In table 3, it is noted that differences of 2.6 psi between tests D-1 and D-2 and 3.4 psi between tests D-1 and D-3 were statistically significant, but the difference of 0.8 psi between tests D-2 and D-3 was not statistically significant.

26. Series E. Test group E-1, consisting of eight penetrations taken before the plate-bearing test was conducted, provided a basis for comparison of the effects of plate penetrations on CPR. The penetrations in this group were made along the outer circumferential row at equal distances from the center of the plate. After the plate-bearing test all of the penetrations were made along lines either normally or diagonally through the center of the test pattern, i.e. center of plate. The posttest penetrations were grouped in sets of four observations from locations at equal distances from the plate center. When the pretest penetration group, E-1, was compared with posttest penetration groups, differences of statistical significance existed for all test groups except E-2, which was located at the outer corners of the test pattern. Comparing posttest groups with each other, differences of statistical significance were indicated in every case. The observations in this series indicate that the penetration of the plate affected CPR in the 0- to 6-in. layer by reducing resistance. The reduction in penetration resistance varied with radial distance from the center of the plate. This apparent effect will be discussed later.

Comparison of average CPR for different areas

27. The results of comparison of mean values of CPR for test groups from different areas of the specimen are shown graphically in fig. 8. Whether or not statistical significance was indicated is shown on the straight line connecting the areas represented by the test groups or series shown. It is noted that differences of statistical significance occurred mainly when comparing test D-1 and series C with other test groups.

Analysis of density data

28. After completion of the cone-penetration tests, sand-specimen unit-weight determinations were made with the box density device. These

unit-weight tests were analytically grouped into four sets of four tests each from the 0- to 2-in. layer (test groups I, II, III, and IV), taken in a symmetrical pattern about the center of series A, B, C, and E, respectively; and one group of five tests (test group V) and one group of four tests (test group VI) from the 6- to 8-in. layer. The data from the unit-weight tests are shown in table 4. The unit weights determined by individual tests ranged from 101.3 to 102.1 lb per cu ft with an average 101.8 lb per cu ft for 16 determinations in the 0- to 2-in. layer, which is 0.6 lb per cu ft less than the average density computed from the volume of the specimen and the total weight of sand used during preparation. The discrepancy between the average unit weights determined by the two methods is believed to be a sampling effect, i.e. either dilation due to penetration of the box density sampler or the previously conducted cone-penetration test. After removing the top 6 in. of the specimen, nine box density samples were made in the 6- to 8-in. layer. Dry unit weights determined in this layer ranged from 100.8 to 102.0 lb per cu ft with an average value of 101.5 lb per cu ft for nine observations. The statistical quantities (s and 95 percent CI for a single observation and for the mean) are shown in table 5 for the various sample groups of unit-weight data.

29. Statistical comparisons of the unit-weight sample groups are shown in table 6. In all the combinations of comparing mean values, the differences in average unit weight were not statistically significant. Comparison between sample groups I through IV indicates that variations in unit weight in the 0- to 2-in. layer were probably within the range of random variation characteristics of the sampling procedure. Similar treatment of sample groups V and VI indicates no detectable differences in unit weight in the 6- to 8-in. layer. By comparing sample groups I and II with V; and comparing III and IV with VI, variations of unit weight with depth were not indicated. When the average of 16 samples from the 0- to 2-in. layer was compared with the average of nine samples from the 6- to 8-in. layer, the difference of 0.28 lb per cu ft was statistically insignificant.

Discussion of Test Results

30. In the foregoing section, differences in observed values of unit weight determined by the box density device were shown to be statistically insignificant. This lack of statistical significance may be interpreted to mean that local variations did not exist, i.e. true uniformity, or that the sampling device was not capable of detecting variations of the magnitude that may have existed. While uniformity has not been defined in terms of tolerable local variations, it appears reasonable to assume that the density samples taken in the specimen were indicative of uniformity for most practical purposes.

31. The results of the cone-penetration tests indicated some significant differences in CPR over the area of the specimens, and statistical analysis indicated the interval within which the average value can be expected to lie for a given probability. The average CPR and the 95 percent CI for the mean for various test groups are plotted against their position relative to the length of the cart in fig. 9a. It is noted in this plot that a horizontal band between 38.5 and 38.6 psi intercepts the 95 percent CI of the mean of all test groups except test D-1 at sta 3+00 and series C at sta 7+50. The upper limit of this band is determined by the lower limit of the CI of test E-1, and the lower limit is determined by the upper limit of the CI of series B. The average value of CPR has a statistical probability of 95 percent of occurring within the CI of the mean. Therefore, the five test groups whose CI includes the horizontal band could have the same average CPR value. However, the two test groups that do not include the horizontal band in the CI of the mean have not more than a 1 in 20 chance of having the same average CPR as the other five test groups, a fact that was demonstrated earlier in the test for statistical significance of differences in CPR (table 3 and fig. 8). Thus, differences in CPR of statistical significance existed over the area of the cart with a zone of lesser stiffness with respect to cone-penetration resistance in the vicinity of sta 3+00, and a zone of greater stiffness was located near sta 7+50.

32. In fig. 9b, the variation of CPR across the cart for the various tests is shown. In every case, CPR values along the center line of the cart were considerably less than values to the right or left of the center line. In series D, it was noted the CPR for penetrations at 2 in. from the side of the cart was slightly less than the CPR at 8 in. from the side.

33. Deviations in CPR, while unit weight was indicated to be relatively uniform, may be attributed to two possible sources.

a. The CPR is sensitive to variations in density differences that cannot be detected by standard unit-weight determinations.

b. The CPR is sensitive to other factors, e.g. lateral pressure or boundary conditions, which cannot be evaluated at this time.

34. Variations in density over small areas of the specimen might have been due to the method of placement of the material and could account for the variations in CPR observed. The box density device would be expected to integrate local deviations over a sampling area of about 48 sq in., while the cone penetrometer samples a much smaller effective area. The sand was placed by showering it through a flexible hose under conditions of constant flow rate and constant free-fall height. While this system is

believed to produce relatively uniform specimens, local variations sensitive only to the cone penetrometer may have developed.

35. The plot of CPR versus width of the cart in fig. 9b might appear to indicate some effect of the cart boundary on CPR, but it is believed the observed variation may be attributed to operator technique in preparation of the specimen. The sand was sprinkled by directing the hose in short strokes over half the cart width in each pass. The apparent weak zones along the center line and near the cart's boundary may be due to irregularities caused by piling up sand at the end of each stroke, which may have produced a slightly lower density in these zones. It is to be noted that no density samples were taken along the center line, so this cannot be verified by data. A new technique for placing sand is being developed which is expected to eliminate operator-induced biases. The device spreads sand over the entire width of the cart on each pass and, when operational, is expected to produce more uniform specimens. A repetition of all or part of the evaluation tests as the opportunities arise in a specimen prepared with the new technique could determine the effect of placement on CPR.

36. A complete correlation of CPR with unit weight was not an objective of this study as other specimens prepared at different densities would be required. However, it is of interest to compare individual unit-weight tests with adjacent CPR tests to determine if any trends over the area of the specimen could be observed. A plot of the average CPR from the four penetrations nearest each box density test versus the measured dry unit weight is shown in the upper part of fig. 10. If one data point to the upper left and two data points to the lower right of the group are disregarded, an increasing CPR with increasing unit weight is suggested; however, the entire range of unit-weight variation was 0.5 lb per cu ft or 1/2 percent of the average density. This range is considered inadequate on which to make definitive conclusions. Comparisons of the average values and 95 percent CI of the mean for four unit-weight samples and 25 penetration tests are shown in the lower portion of fig. 10. It is noted that all the observed unit weights plotted in the upper portion of fig. 10 fall within the statistical interval established in the lower portion. Thus, the equipment and procedure used in this study did not detect significant local variations that would lead to a correlation of CPR with density.

Investigation of Irregularities in Specimen

37. The utility of using the cone for detection of hidden irregularities was demonstrated largely by accident. During placement of the layer from 6 to 8 in. from the surface of the specimen, a large heavy chain fell

from the hoist holding the sand sprinkler onto the surface of the sand in the vicinity of sta 4+00. The effect of this disturbance was distinctly detected in the penetration-resistance curves from series B. Two records of penetration resistance versus depth from series B are shown in fig. 11. Penetration No. 11 is a typical record with penetration resistance increasing monotonically with depth, while in penetration No. 12, a dip in the trace occurs between depths of 8 and 10 in. Similar records were obtained in about half of the penetrations in series B and were grouped in an area on the left side of the test pattern. The deviation from the typical test record is believed due to disturbance caused by the falling chain, which formed a lens of looser sand. However, the magnitude of the density variation is not known, since two box density samples at the 6-in. depth within the suspected region indicated no detectable variations in unit weight. The deviation from normal CPR behavior occurred at a depth greater than 6 in.; therefore, the statistical analysis of the 0- to 6-in. average CPR was not affected.

38. While investigation of local irregularities of this nature was not included in the objectives, the above observations illustrate the usefulness of the cone penetrometer in assessing specimen uniformity. The detection of similar behavior in a test specimen could be sufficient justification for rejection of a planned test area prior to test.

Application of Results of Study

39. The analysis of CPR data in series A indicated the effect of the number of observations on statistical reliability. Since only a small variation in the average value of CPR was observed (see paragraph 22 and fig. 9), the statistical quantities can be examined as nondimensional ratios $s/\bar{x}$ (coefficient of variation), $ts/\bar{x}$ (95 percent CI of single observation ratio), and $ts_m/\bar{x}$ (95 percent CI of mean ratio). A plot of these ratios versus number of observations is shown in fig. 12. For four observations, a single observation would be expected to be within 20 percent of the true mean, and the computed mean would be within 10 percent of true mean 95 percent of the time. Where 25 observations were made, the 95 percent CI of a single observation ratio and 95 percent CI of the mean ratio reduced to 12.5 and 2.5 percent, respectively. Increasing the number of observations beyond 25 did not significantly decrease the confidence intervals.

40. The results of series B and C appeared to indicate the spacing of penetration test on a 6-in.-square grid produced no detectable interaction effects on CPR. For the purpose of assessing the area around a

footing test such as the static plate-bearing test in this study, eight penetrations using a 6-in.-grid spacing in a symmetrical pattern have been used. For eight observations, the 95 percent CI for the mean ratio is approximately 6 percent, a degree of precision which should be adequate for the footing studies. For comparison, the computed statistical ratios for test E-1, which had eight observations, are:

$s/\bar{x}$: 4.1 percent

$ts/\bar{x}$: 9.7 percent

$ts_m/\bar{x}$: 3.4 percent

These values are all less than the limits determined from series A (see fig. 12). Thus, the practice of taking eight penetrations prior to making a footing test in a particular area similar to that used in test E-1 is considered adequate and should be continued.

Effect of Plate Penetration on CPR

41. The penetration of the 6-in.-square plate (driven approximately 3 in. into the specimen by static loading) produced visible disturbance over a distinct area surrounding the footing. An upheaval of the surface of as much as 1 in. was observed. Penetrations made both along normal and diagonal lines through the test pattern center indicated that CPR decreased with decrease in distance from the center of the plate. In fig. 13, the ratio of CPR of a particular posttest penetration group to the CPR observed prior to the plate-bearing test (E-1) is plotted against radial distance from the footing center. The plot shows that CPR in the disturbed zone was reduced as much as 55 percent. While definitive conclusions cannot be drawn from a single case, the fact that a single curve can be drawn through the four data points tends to suggest that the gross effects on CPR may be independent of plate orientation. Undoubtedly, the degree of disturbance and its resulting effect on CPR are directly related to depth of penetration; thus, an extensive investigation would be required to develop techniques for evaluating and interpreting CPR taken in a disturbed zone. For the particular case observed, it was found that only observations made approximately 18 in. from the center of the plate were indicative of the pretest condition. Therefore, CPR observations made within 18 in. of the plate center after a plate loading test cannot be considered indicative of the pretest condition of the specimen, even along the diagonals, and the significance of the reduced CPR in terms of density cannot be evaluated at the present time without a correlation of CPR and density. Evaluation of variations in CPR produced by plate loading disturbance is beyond the scope of this investigation.

Conclusions and Recommendations

Conclusions

42. The results of the evaluation tests and the subsequent analysis indicate that the cone-penetration test can be used to evaluate relative uniformity of a dry sand specimen if the random nature of CPR data is recognized and properly considered. The following specific conclusions were drawn as a result of this study:

a. The spacing of penetration on a 6-in.-square grid pattern produced negligible interaction effects on CPR.

b. The specimen used was remarkably uniform, although zones of greater and lesser stiffness with respect to cone-penetration resistance were detected. It is believed that the observed variations in CPR were probably due to minor variations in density not detectable by standard methods of measurement, although other factors not known at the time could have contributed to the variations. The variations, particularly the distribution of CPR across the specimen, are believed to have been induced largely by the method of placement of the sand. Modification of the placement technique to reduce operator-induced bias is anticipated, and penetration tests in specimens prepared by the new method that sprinkles the entire width of the specimen with each pass will clarify some points now in doubt.

c. The somewhat erratic nature of CPR data emphasized the need for making an adequate number of observations for a statistically sound evaluation. Within a particular area, four penetrations produced a computed mean value of CPR that should be within 10 percent of the true mean value; the average of eight observations should be within 6 percent of the true value. Increasing the number of observations to 25 would be expected to produce a computed mean value that deviated not more than 2.5 percent from the true mean value.

d. The penetration of the plate in the static plate-bearing test produced disturbances within the specimen varying with depth and distance from the footing. Posttest penetrations cannot validly be used to evaluate the preplate-bearing-test condition. The loosened condition in the disturbed zones prevents reliable interpretation of CPR; thus, these data have limited usefulness.

e. The cone penetrometer is useful for detecting irregularities within the specimen. An accidental disturbance produced during preparation of the specimen was very clearly detected and located.

Recommendations

43. Based on the results of this study, it is recommended that cone-penetration data be taken in each specimen before conducting other types of tests to evaluate the relative uniformity and locate possible hidden defects. A minimum of eight penetrations should be taken in each area at a spacing of not less than 6 in. In footing studies using small-scale plates, the disturbance due to plate penetrations precludes evaluation of the pretest uniformity following the test; therefore, posttest penetrations are not recommended.

44. Every opportunity should be utilized to extend the range of data and useful applications, i.e. particularly, to establish the statistical range of CPR for a given unit weight. A separate study to obtain additional data is not considered justified, but much information from cone-penetration data in connection with other studies can be collected.

45. Should the opportunity for obtaining penetration test data arise, a specific plan of tests to evaluate the effects of placement on CPR and to attempt to develop a correlation between CPR and unit weight is recommended as follows:

a. Number of specimens. At least four specimens are needed: one specimen that duplicates the unit weight of 102.4 lb per cu ft for the specimens used in this study, one specimen with a unit weight of approximately 1 lb per cu ft greater than that used in this study, and two specimens with unit weights of approximately 2 and 5 lb per cu ft less than that used in this study.

b. Number of tests. In each specimen, two sets of 25 penetrations on a 5-by-5 matrix with a 6-in. spacing are required. Data collected from other phases of the overall study have indicated that static plate-bearing-test results are indicative of overall uniformity of specimens; therefore, at least two static plate-bearing tests should be conducted in each specimen.

46. The collection of CPR data should be included in continuing programs which utilize prepared specimens of granular soils. The cone penetrometer appears to be a suitable device for the nondestructive assessment of the uniformity of a prepared specimen of dry sand prior to

conducting other tests. However, other systems, such as vane shear devices, nuclear density probes, etc., should be evaluated for this purpose as opportunities arise.

Table 1 (Continued)

Series C									
	Location		0-6 In.						
Penetration No.	Station	Offset in.	Avg CPR psi	Analytical Test Grouping C-1	C-2	C-3	C-4	C-5	C-6
1	7+50	20	36.62	x					
2	6+50	8	43.36		x				
3	6+50	32	43.60		x				
4	8+50	8	42.13		x				
5	8+50	32	43.08		x				
6	8+50	20	39.13			x			
7	7+50	8	43.68			x			
8	7+50	32	44.32			x			
9	6+50	20	40.57			x			
10	7+00	14	42.64				x		
11	7+00	26	42.01				x		
12	8+00	14	36.10				x		
13	8+00	26	36.74				x		
14	8+00	20	34.15					x	
15	7+50	14	39.41					x	
16	7+50	26	39.33					x	
17	7+00	20	36.62					x	
18	7+00	8	41.45						x
19	7+00	32	41.61						x
20	6+50	14	40.69						x
21	6+50	26	39.69						x
22	8+00	8	41.73						x
23	8+00	32	41.53						x
24	8+50	14	41.01						x
25	8+50	26	40.89						x

(Continued)

Table 1 (Continued)

Series D						
	Location		0-6 In.	Analytical Test Grouping		
Penetration No.	Station	Offset in.	Avg CPR psi	D-1	D-2	D-3
1	3+00	2	36.54	x		
2	3+00	8	37.90	x		
3	3+00	14	34.35	x		
4	3+00	20	34.19	x		
5	3+00	26	37.74	x		
6	3+00	32	35.58	x		
7	3+00	38	34.79	x		
8	6+00	2	38.89		x	
9	6+00	8	39.17		x	
10	6+00	14	37.94		x	
11	6+00	20	35.06		x	
12	6+00	26	37.98		x	
13	6+00	32	39.93		x	
14	6+00	38	40.25		x	
15	9+00	2	40.05			x
16	9+00	8	40.41			x
17	9+00	14	39.85			x
18	9+00	20	36.34			x
19	9+00	26	39.17			x
20	9+00	32	39.87			x
21	9+00	38	39.41			x

(Continued)

Table 1

Cone-Penetration Resistance Data

Series A							
	Location		0-6 In.	Analytical Test Grouping			
Penetration No.	Station	Offset in.	Avg CPR psi	A-1	A-2	A-3	Series A
1	0+50	8	34.15	x	x	x	x
2	0+50	14	36.74	x	x	x	x
3	0+50	20	37.42		x	x	x
4	0+50	26	34.31			x	x
5	0+50	32	40.33				x
6	1+00	8	38.93	x	x	x	x
7	1+00	14	39.57	x	x	x	x
8	1+00	20	36.58		x	x	x
9	1+00	26	40.73			x	x
10	1+00	32	42.84				x
11	1+50	8	41.89		x	x	x
12	1+50	14	40.97		x	x	x
13	1+50	20	34.98		x	x	x
14	1+50	26	35.54			x	x
15	1+50	32	38.18				x
16	2+00	8	40.57			x	x
17	2+00	14	40.37			x	x
18	2+00	20	37.94			x	x
19	2+00	26	39.89			x	x
20	2+00	32	39.53				x
21	2+50	8	38.06				x
22	2+50	14	38.62				x
23	2+50	20	36.82				x
24	2+50	26	37.66				x
25	2+50	32	36.02				x

(Continued)

Table 1 (Continued)

Penetration No.	Location Station	Location Offset in.	0-6 In. Avg CPR psi	Analytical Test Grouping B-1	B-2	B-3	B-4	B-5
Series B								
1	4+50	20	35.66	x				
2	4+50	14	39.57		x			
3	4+50	26	40.25		x			
4	5+00	20	39.53		x			
5	4+00	20	38.26		x			
6	4+00	14	33.43			x		
7	4+00	26	37.02			x		
8	5+00	14	38.26			x		
9	5+00	26	37.38			x		
10	4+50	8	38.69				x	
11	4+50	32	36.06				x	
12	5+50	20	35.22				x	
13	3+50	20	36.54				x	
14	5+50	8	39.73					x
15	5+50	14	37.98					x
16	5+50	26	37.62					x
17	5+50	32	40.33					x
18	5+00	8	39.65					x
19	5+00	32	39.45					x
20	4+00	8	39.69					x
21	4+00	32	38.69					x
22	3+50	8	39.1[illegible]					x
23	3+50	14	36.62					x
24	3+50	26	37.10					x
25	3+50	32	37.26					x

(Continued)

Table 1 (Concluded)

Series E								
	Location		0-6 In.					
Penetration No.	Station	Offset in.	Avg CPR psi	Analytical Test Grouping E-1*	E-2**	E-3**	E-4**	E-5**
1	11+50	14	38.14	x				
2	11+50	26	38.54	x				
3	11+00	8	41.73	x				
4	11+00	32	38.38	x				
5	10+00	8	41.89	x				
6	9+50	14	40.53	x				
7	9+50	26	40.57	x				
8	10+00	32	39.01	x				
9	11+50	8	37.86		x			
10	11+50	32	37.34		x			
11	11+00	14	30.08			x		
12	11+00	26	28.28			x		
13	10+00	14	27.13			x		
14	10+00	26	25.73			x		
15	9+50	8	42.01		x			
16	9+50	32	38.14		x			
17	10+50	8	36.94				x	
18	10+50	32	34.91				x	
19	9+50	20	34.07				x	
20	11+50	20	34.63				x	
21	10+50	26	18.27					x
22	10+50	14	18.55					x
23	11+00	20	18.03					x
24	10+00	20	16.75					x
25	10+50	20	***					x

* Penetrations made prior to static plate-bearing test.
** Penetrations made after static plate-bearing test.
*** Not computed.

Table 2

Statistical Analysis of Cone-Penetration-Resistance Data

Test No.	No. Obs n	0-6 In. Avg CPR $\bar{x}$	Est Std Dev s	Est Std Dev of Mean s_m	95% CI t	95% CI Single Obs ts	95% CI Mean ts_m
				Series A			
A-1	4	37.35	2.452	1.226	3.182	± 7.80	± 3.90
A-2	9*	37.91	2.629	0.876	2.306	± 6.06	± 2.02
A-3	16*	38.16	2.552	0.638	2.131	± 5.44	± 1.36
Series A	25*	38.35	2.346	0.469	2.064	± 4.84	± 0.97
				Series B			
B-1	1	35.66					
B-2	4	39.40	0.830	0.415	3.182	± 2.64	± 1.32
B-3	4	36.52	2.126	1.063	3.182	± 6.76	± 3.38
B-4	4	36.63	1.479	0.740	3.182	± 4.71	± 2.35
B-2, -3 & -4	12	37.52	1.990	0.574	2.201	± 4.38	± 1.26
B-5	12	38.61	1.209	0.349	2.201	± 2.66	± 0.77
Series B	25	37.97	1.622	0.324	2.064	± 3.35	± 0.67
				Series C			
C-1	1	36.62					
C-2	4	43.04	0.644	0.322	3.182	± 2.05	± 1.03
C-3	4	41.93	2.481	1.240	3.182	± 7.89	± 3.95
C-4	4	39.37	3.397	1.699	3.182	±10.81	± 5.41
C-5	4	37.38	2.513	1.257	3.182	± 8.00	± 4.00
C-6	8	41.07	0.673	0.238	2.365	± 1.59	± 0.56
Series C	25	40.48	2.740	0.548	2.064	± 5.66	± 1.13
				Series D			
D-1	7	35.87	1.552	0.587	2.447	± 3.80	± 1.44
D-2	7	38.46	1.738	0.657	2.447	± 4.25	± 1.61
D-3	7	39.30	1.368	0.517	2.447	± 3.35	± 1.27
Series D	21	37.88	2.059	0.449	2.086	± 4.30	± 0.94
				Series E			
E-1**	8	39.85	1.642	0.581	2.365	± 3.88	± 1.37
E-2***	4	38.84	2.141	1.071	3.182	± 6.81	± 3.41
E-3***	4	27.81	1.841	0.921	3.182	± 5.86	± 2.93
E-4***	4	35.14	1.251	0.626	3.182	± 3.98	± 1.99
E-5***	4	17.90	0.796	0.398	3.182	± 2.53	± 1.26

* Includes observations in preceding set.
** Penetrations made prior to plate-bearing test.
*** Penetrations made after plate-bearing test completed.

Table 3

Comparison of Mean Values of CPR for Various Tests

Means Compared		Total No. of Obs $n_1 + n_2$	Difference in Mean Values (Avg CPR) psi $\bar{x}_1 - \bar{x}_2$	Std Error $s_{\bar{\delta}}$	Degrees of Freedom n_1+n_2-2	95% Conf Level t	95% CI for Dif of Means $ts_{\bar{\delta}}$	Is Difference in Mean Values Statistically Significant?
Series A	Series B	50	0.38	0.570	48	2.013	1.15	No
Series A	Series C	50	2.13	0.721	48	2.013	1.45	Yes
Series B	Series C	50	2.51	0.637	48	2.013	1.28	Yes
B-2	B-3	8	2.88	1.141	6	2.447	2.79	Yes
B-3	B-4	8	0.11	1.292	6	2.447	3.16	No
B-2, -3, & -4	B-5	24	1.09	0.672	22	2.074	1.39	No
C-2	C-3	8	1.11	1.281	6	2.447	3.13	No
C-4	C-5	8	1.98	2.113	6	2.447	5.17	No
D-1	D-2	14	2.59	0.881	12	2.179	1.92	Yes
D-1	D-3	14	3.43	0.782	12	2.179	1.70	Yes
D-2	D-3	14	0.84	0.836	12	2.179	1.82	No
E-1	E-2	12	1.04	1.222	10	2.228	2.72	No
E-2	E-3	8	11.[illegible]3	1.413	6	2.447	3.46	Yes
E-2	E-4	8	3.[illegible]0	1.240	6	2.447	3.04	Yes
E-4	E-5	8	17.[illegible]4	0.742	6	2.447	1.82	Yes
A-2	E-1	17	1.94	1.051	15	2.131	2.24	No
C-6	E-1	16	1.22	0.628	14	2.145	1.34	No
Series A	D-1	32	2.48	0.751	30	2.042	1.53	Yes
Series B	D-1	32	2.10	0.670	30	2.042	1.37	Yes
Series B	D-2	32	0.49	0.733	30	2.042	1.50	No
Series C	D-2	32	2.02	0.856	30	2.042	1.75	Yes
Series C	D-3	32	1.18	0.694	30	2.042	1.42	No
D-3	E-1	15	0.55	0.777	13	2.160	1.68	No

Table 4

Unit Weight Data - Box Density Sampler

Layer Depth in.	Sample Group	Test No.	Location Station	Location Offset in.	Dry Unit Weight pcf γ_d
0-2	I	1	0+75	11	101.97
		2	0+75	29	101.94
		3	2+25	11	101.90
		4	2+25	29	101.75
		Avg			101.89
0-2	II	5	3+75	11	102.04
		6	3+75	29	101.63
		7	5+25	11	101.81
		8	5+25	29	101.65
		Avg			101.79
0-2	III	9	6+75	11	102.03
		10	6+75	29	101.87
		11	8+25	11	101.53
		12	8+25	29	102.06
		Avg			101.87
0-2	IV	13	9+75	11	101.60
		14	9+75	29	102.00
		15	11+25	11	102.07
		16	11+25	29	101.30
		Avg			101.74
0-2	I-IV	Avg			101.82
6-8	V	1	0+75	17	100.84
		2	2+25	17	101.66
		3	3+75	11	102.04
		4	4+25	29	101.84
		5	5+25	17	101.29
		Avg			101.53
6-8	VI	6	6+75	23	101.28
		7	8+25	23	101.44
		8	9+75	11	101.67
		9	11+25	29	101.82
		Avg			101.55
6-8	V-VI	Avg			101.54

Table 5

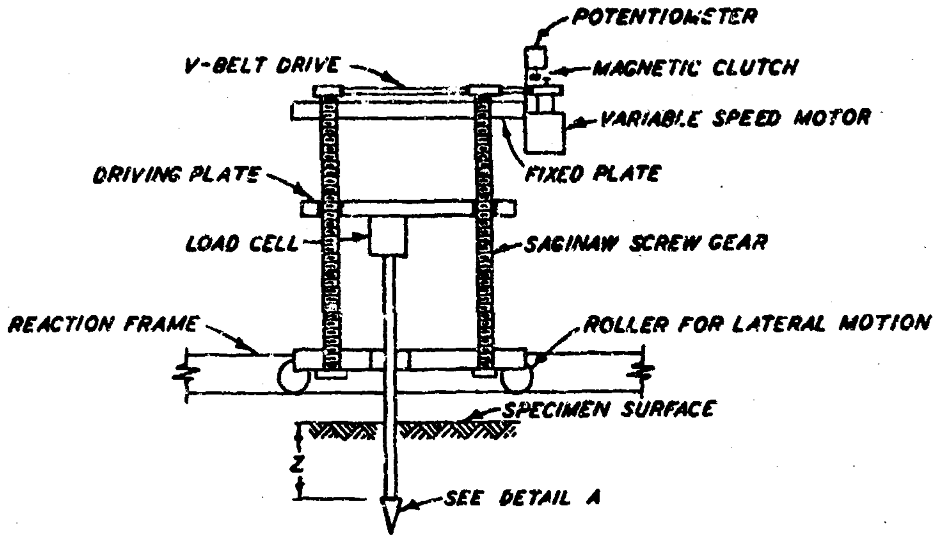
Statistical Analysis of Unit Weight Data

Depth of Sample in.	Sample Group	n	Avg Dry Unit Wt pcf $\bar{X}$	s	s_m	95% CI t	95% CI Single Obs, ts	95% CI Mean ts_m
0-2	I	4	101.89	0.097	0 049	3.182	± 0.31	± 0.16
	II	4	101.79	0.190	0.095	3.182	± 0.60	± 0.30
	III	4	101.87	0.243	0.121	3.182	± 0.77	± 0.39
	IV	4	101.74	0.360	0.180	3.182	± 1.15	± 0.57
	I-IV	16	101.82	0.225	0.056	2.131	± 0.48	± 0.12
6-8	V	5	101.53	0.476	0.213	2.776	± 1.32	± 0.59
	VI	4	101.55	0.240	0.120	3.182	± 0.76	± 0.38
	V-VI	9	101.54	0.367	0.121	2.306	± 0.85	± 0.28

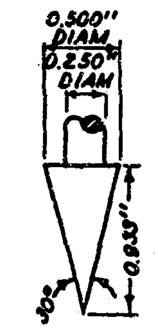
Table 6

Comparison of Mean Values of Unit Weight - Box Density Sampler Data

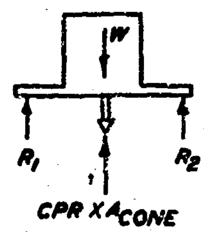
Means Compared		Total No. of Obs $n_1 + n_2$	Difference in Mean Values (Avg γ_d) pcf $\bar{x}_1 - \bar{x}_2$	Std Error s_δ	Degrees of Freedom $n_1 + n_2 - 2$	95% Conf Level t	95% CI for Dif of Means ts_δ	Is Difference in Mean Values Statistically Significant?
I	II	8	0.10	0.107	6	2.447	0.26	No
I	III	8	0.002	0.130	6	2.447	0.32	No
I	IV	8	0.15	0.187	6	2.447	0.46	No
II	III	8	0.08	0.154	6	2.447	0.38	No
II	IV	8	0.05	0.203	6	2.447	0.50	No
III	IV	8	0.13	0.217	6	2.447	0.53	No
V	IV	9	0.02	0.244	7	2.365	0.58	No
I	V	9	0.35	0.219	7	2.365	0.52	No
II	V	9	0.25	0.233	7	2.365	0.55	No
III	VI	8	0.32	0.170	6	2.447	0.42	No
IV	VI	8	0.19	0.216	6	2.447	0.53	No
I-IV	V-VI	25	0.28	0.133	23	2.069	0.28	No



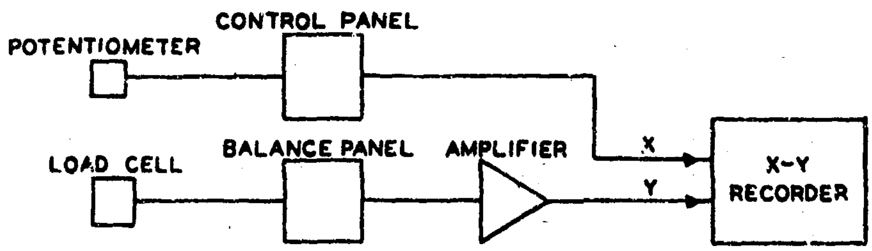
a. SCHEMATIC DIAGRAM OF MECHANICAL SYSTEM



DETAIL A



b. FREE BODY OF SYSTEM

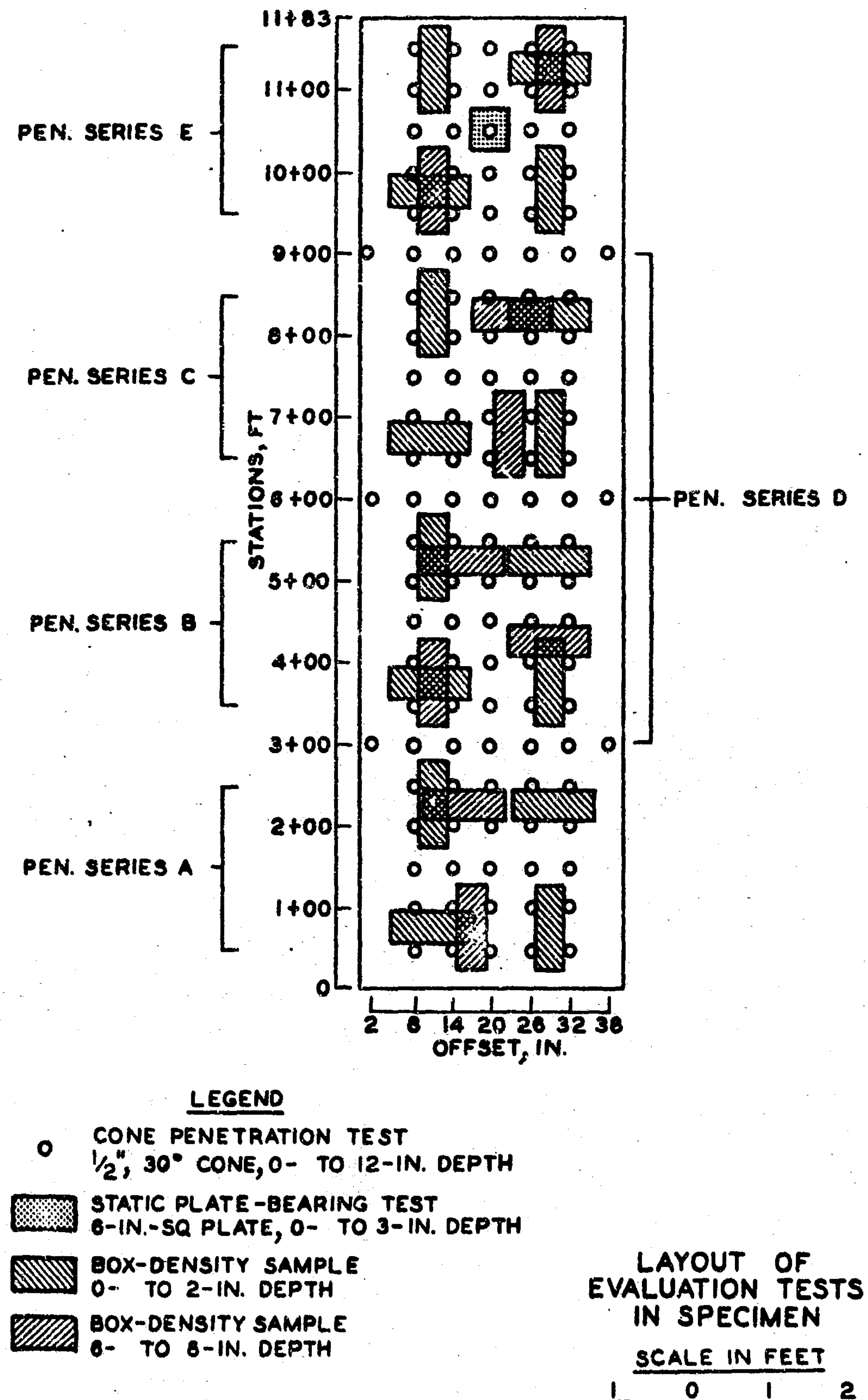


INSTRUMENT	MANUFACTURER	MODEL OR TYPE	SERIAL NO.
POTENTIOMETER	BECKMAN INST	10-TURN HELICAL	
LOAD CELL	ALINCO	200-LB CAP	34132
AMPLIFIER	CEC	MODEL 1-1[illegible]	17012
RECORDER	MOSELEY	MODEL 35C	170

c. SCHEMATIC DIAGRAM OF INSTRUMENTATION AND RECORDING COMPONENTS

EQUIPMENT DETAILS
CONE PENETRATION SYSTEM

FIG. 1



LAYOUT OF EVALUATION TESTS IN SPECIMEN

FIG. 2

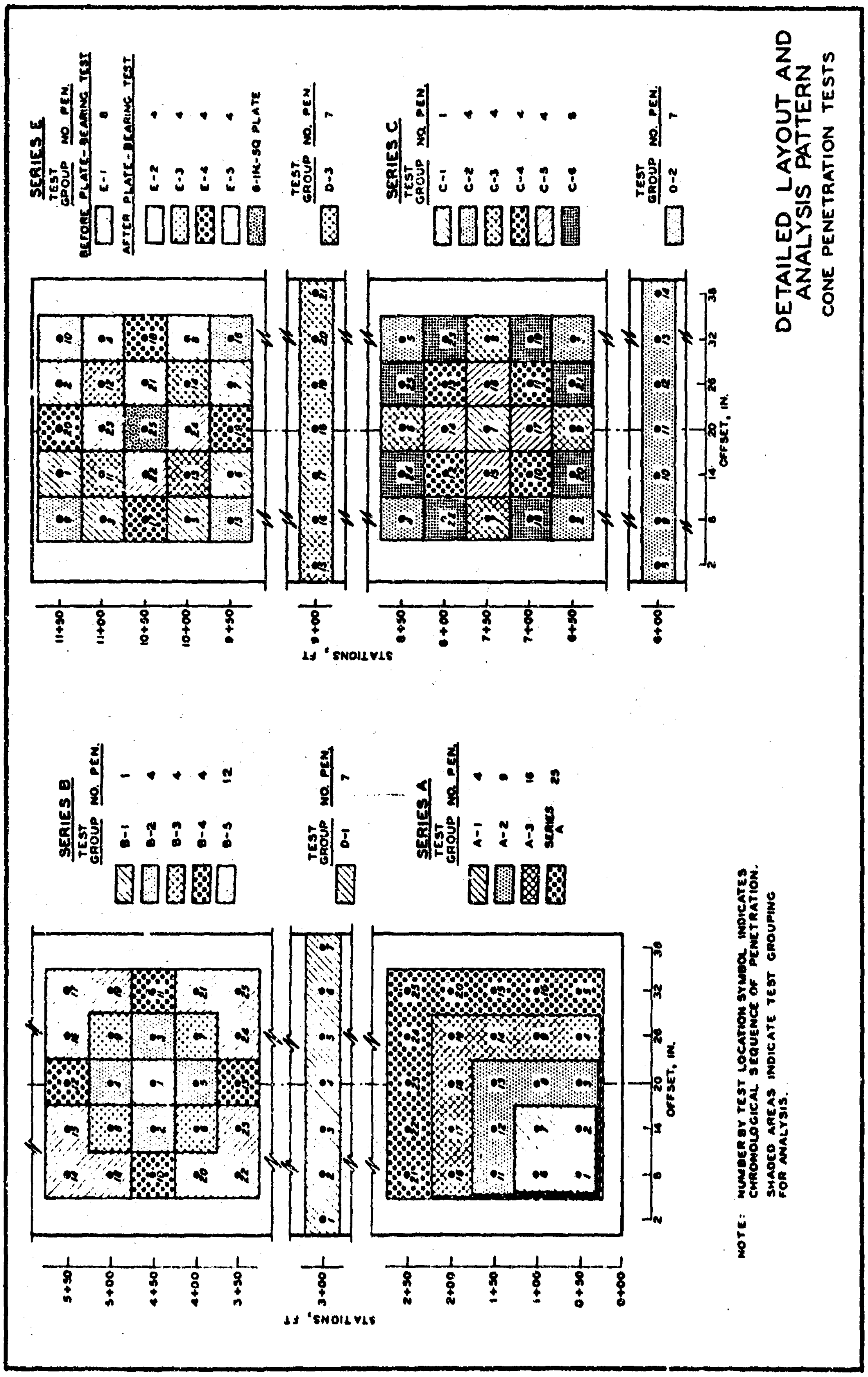

DETAILED LAYOUT AND ANALYSIS PATTERN
CONE PENETRATION TESTS
SERIES E
TEST GROUP NO. PEN.
BEFORE PLATE-BEARING TEST
E-1 8
AFTER PLATE-BEARING TEST
E-2 4
E-3 4
E-4 4
E-5 4
6-IN-SQ PLATE
TEST GROUP NO. PEN.
D-3 7
SERIES C
TEST GROUP NO. PEN.
C-1 1
C-2 4
C-3 4
C-4 4
C-5 4
C-6 8
TEST GROUP NO. PEN.
D-2 7
SERIES B
TEST GROUP NO. PEN.
B-1 1
B-2 4
B-3 4
B-4 4
B-5 12
TEST GROUP NO. PEN.
D-1 7
SERIES A
TEST GROUP NO. PEN.
A-1 4
A-2 8
A-3 16
SERIES A 25
STATIONS, FT
OFFSET, IN.
NOTE: NUMBER BY TEST LOCATION SYMBOL INDICATES CHRONOLOGICAL SEQUENCE OF PENETRATION.
SHADED AREAS INDICATE TEST GROUPING FOR ANALYSIS.

FIG. 3

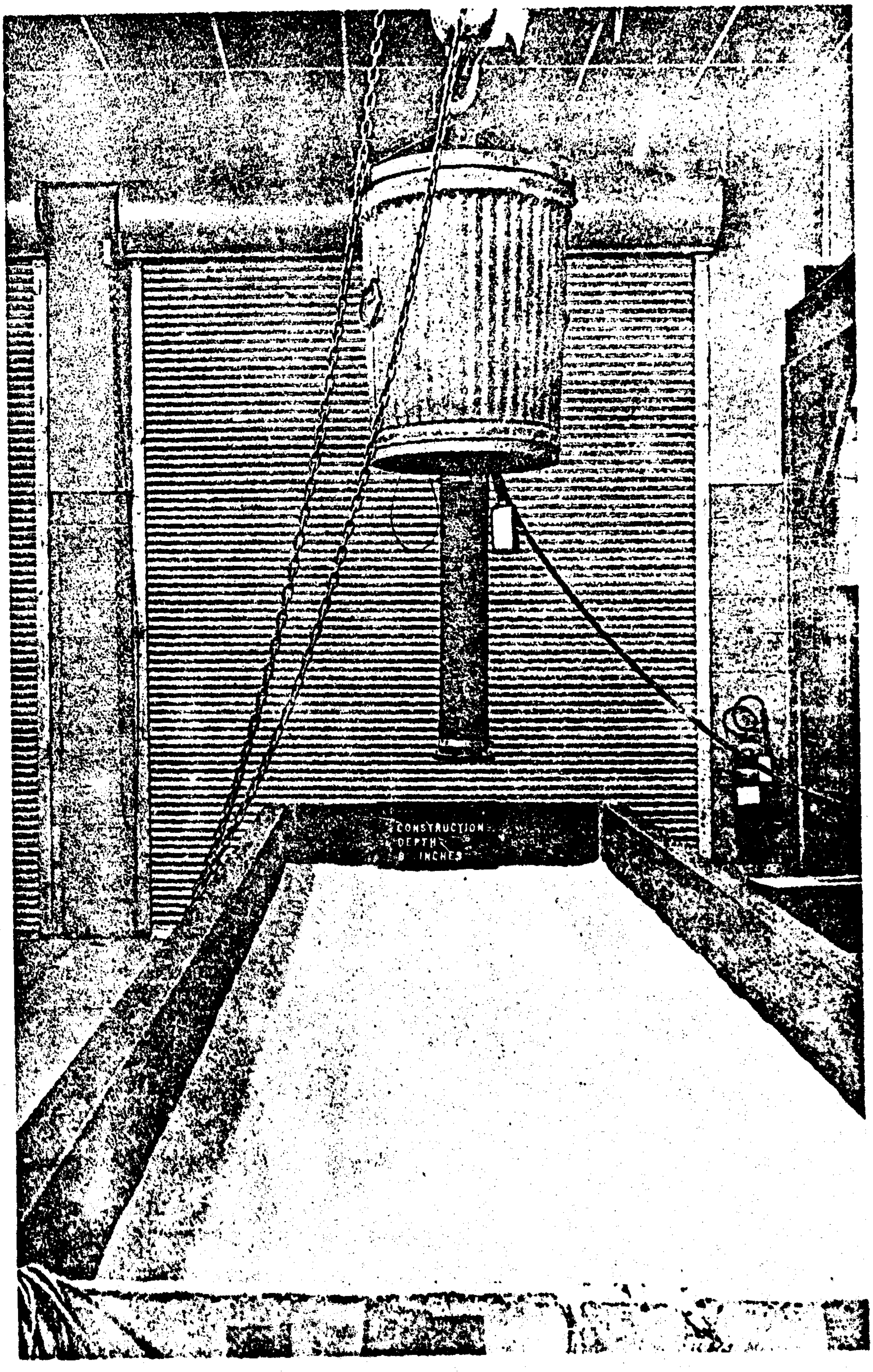
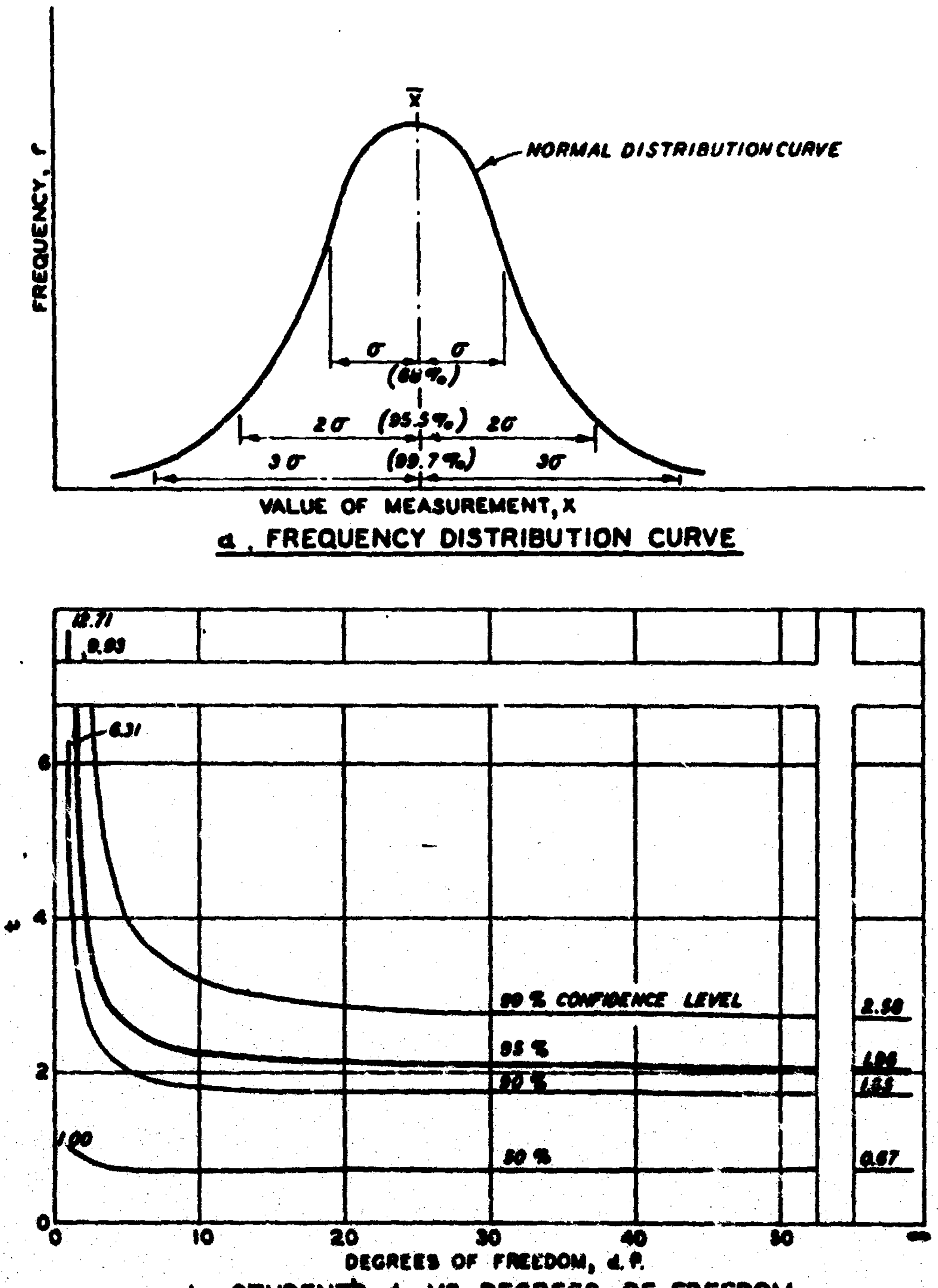


Fig. 4. Single-orfice sand sprinklcr with mobile cart containing partially completed specimen

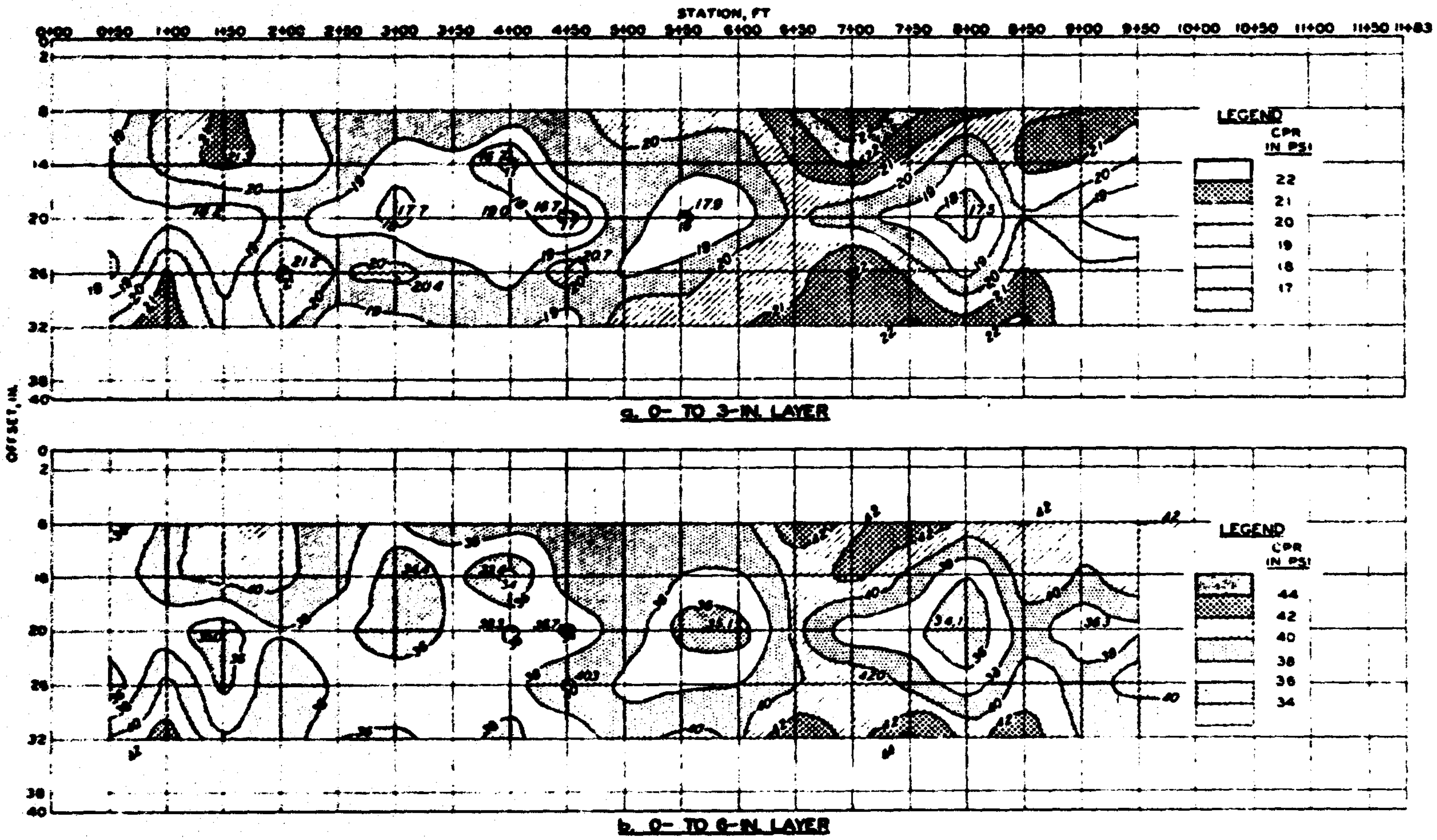


a. FREQUENCY DISTRIBUTION CURVE

b. STUDENTS t VS DEGREES OF FREEDOM

THEORETICAL STATISTICAL RELATIONS

FIG. 5



CONTOURS OF EQUAL
CONE PENETRATION RESISTANCE

FIG. 6

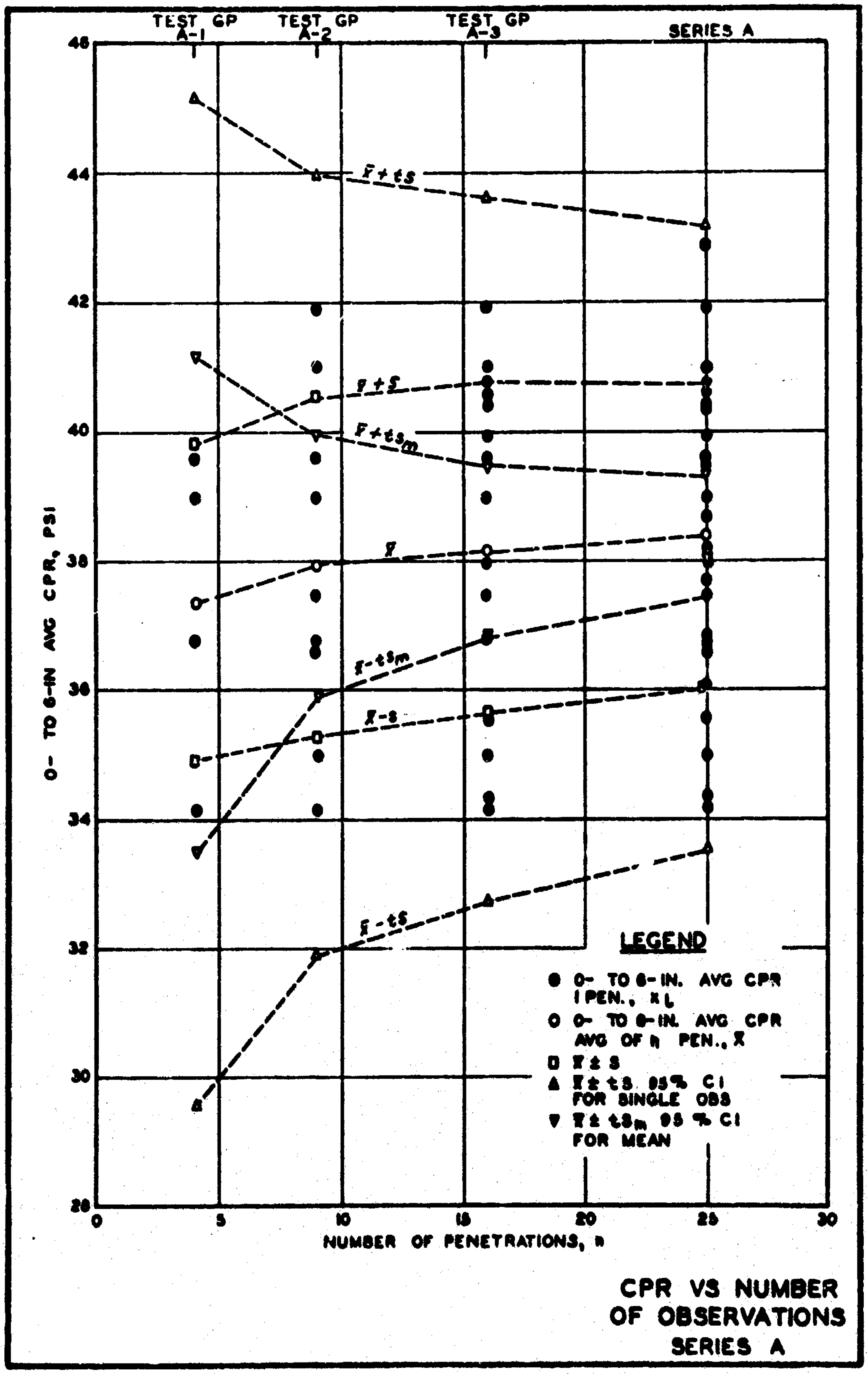
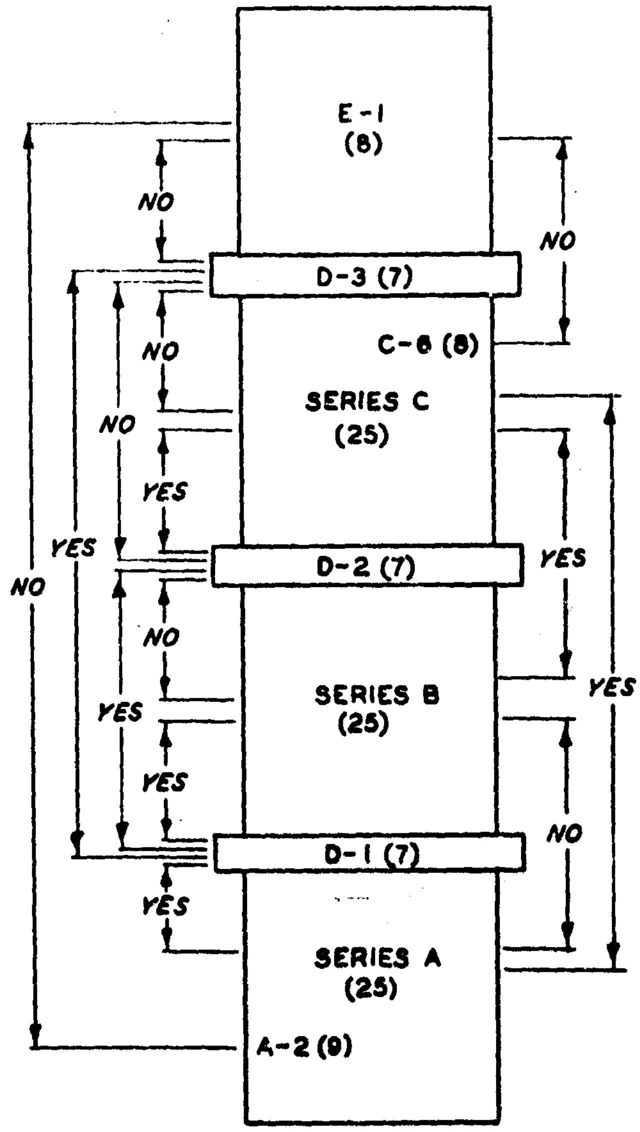

TEST GP A-1
TEST GP A-2
TEST GP A-3
SERIES A
0- TO 6-IN AVG CPR, PSI
NUMBER OF PENETRATIONS, n
LEGEND
0- TO 6-IN. AVG CPR 1 PEN., x_i
0- TO 6-IN. AVG CPR AVG OF n PEN., $\bar{x}$
$\bar{x} \pm s$
$\bar{x} \pm ts$ 95% CI FOR SINGLE OBS
$\bar{x} \pm ts_m$ 95% CI FOR MEAN
CPR VS NUMBER OF OBSERVATIONS SERIES A

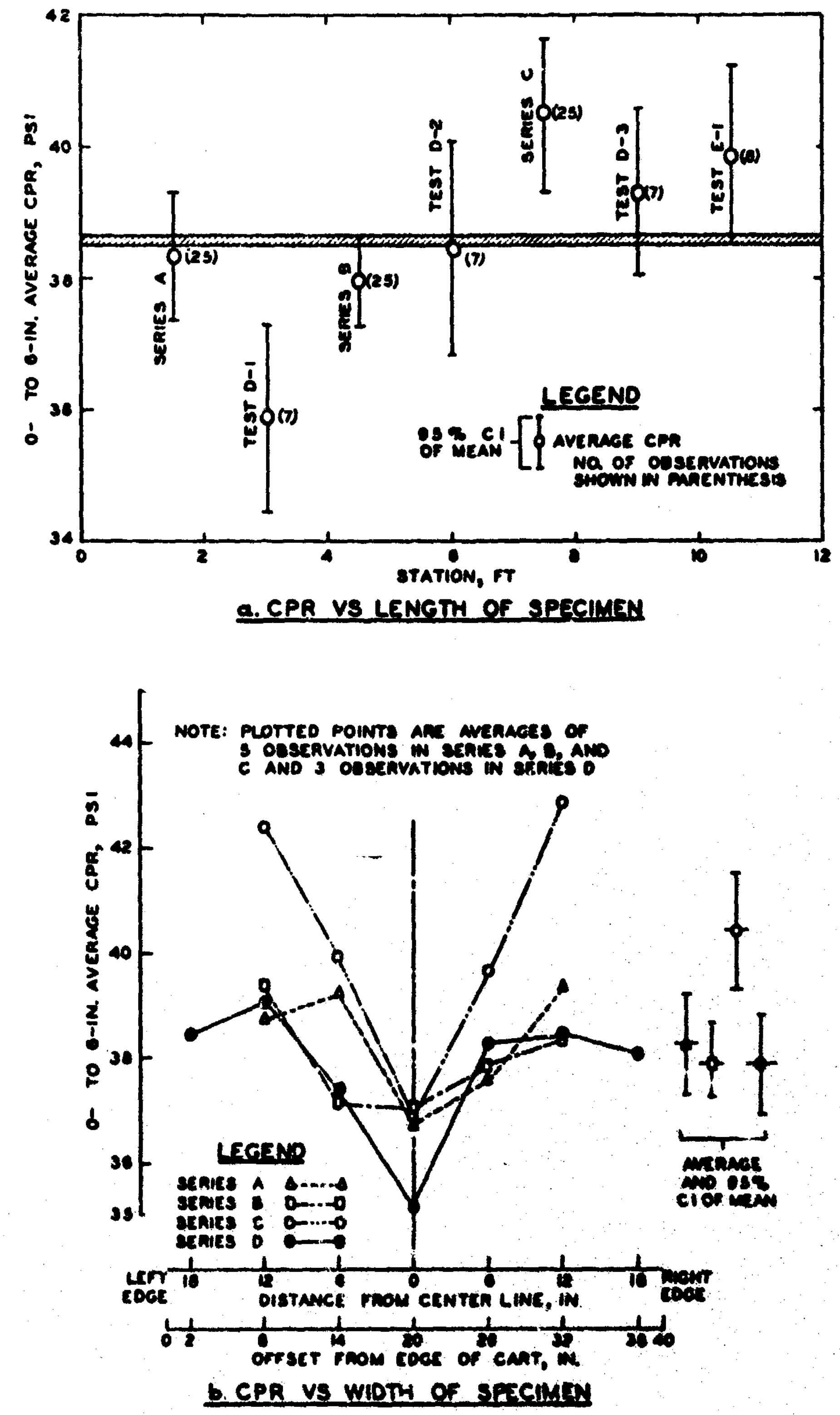
FIG. 7



NOTE: NUMBER OF PENETRATIONS IN SET SHOWN IN PARENTHESIS.

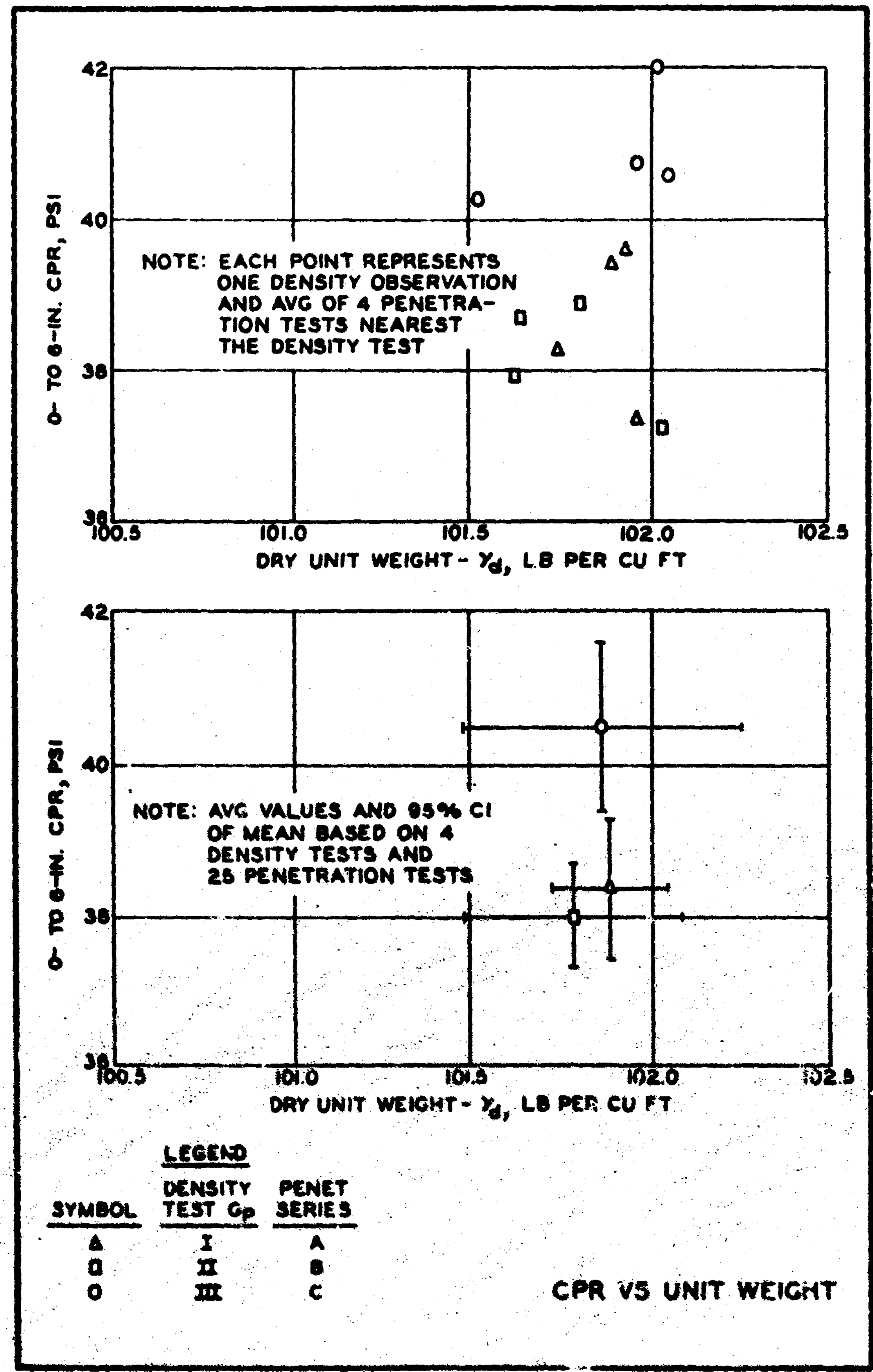
TESTS FOR STATISTICAL SIGNIFICANCE OF DIFFERENCE IN AVG CPR
VARIOUS TEST GROUPS

FIG. 8



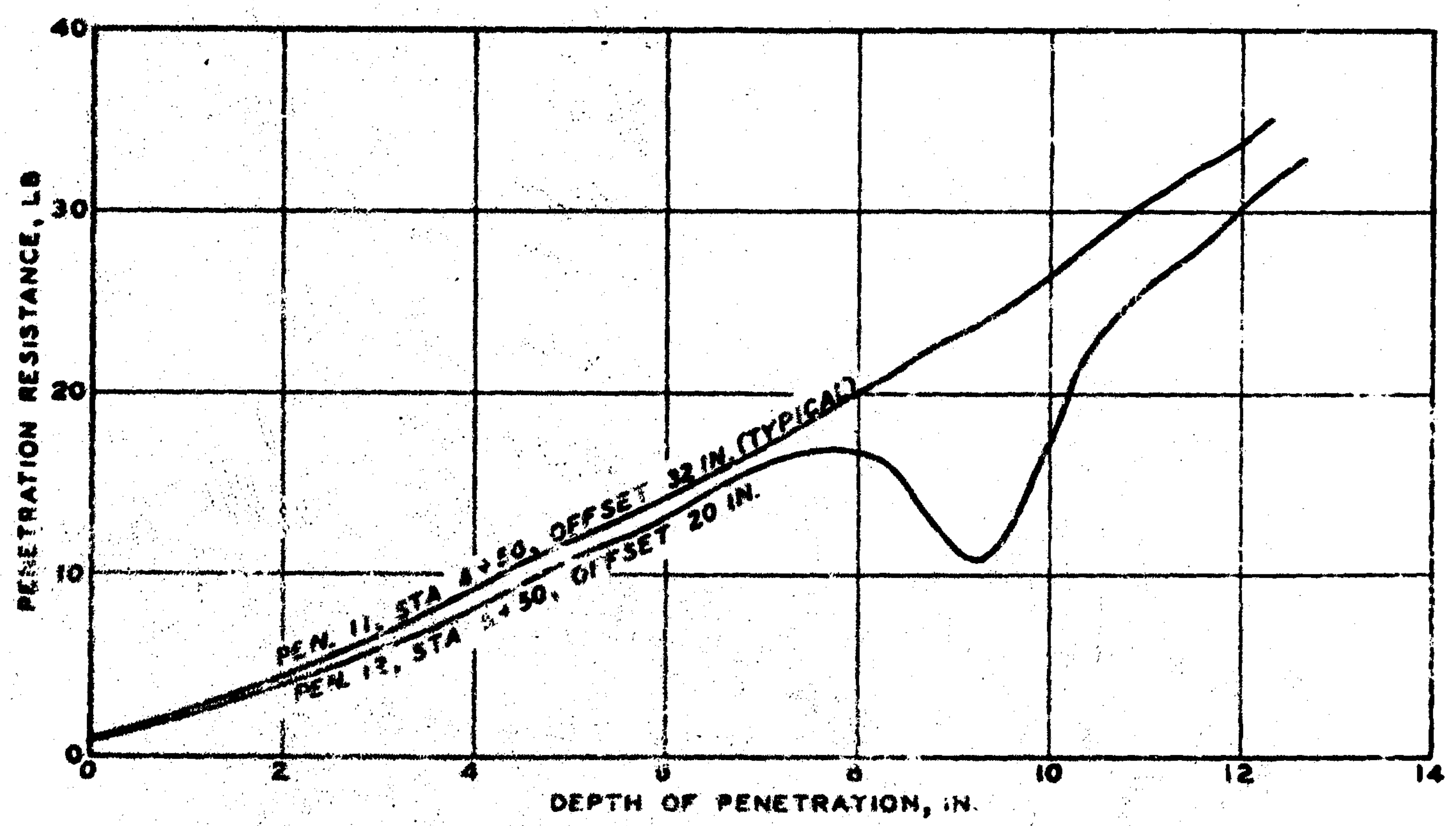
VARIATIONS OF CPR IN SPECIMEN

FIG. 9



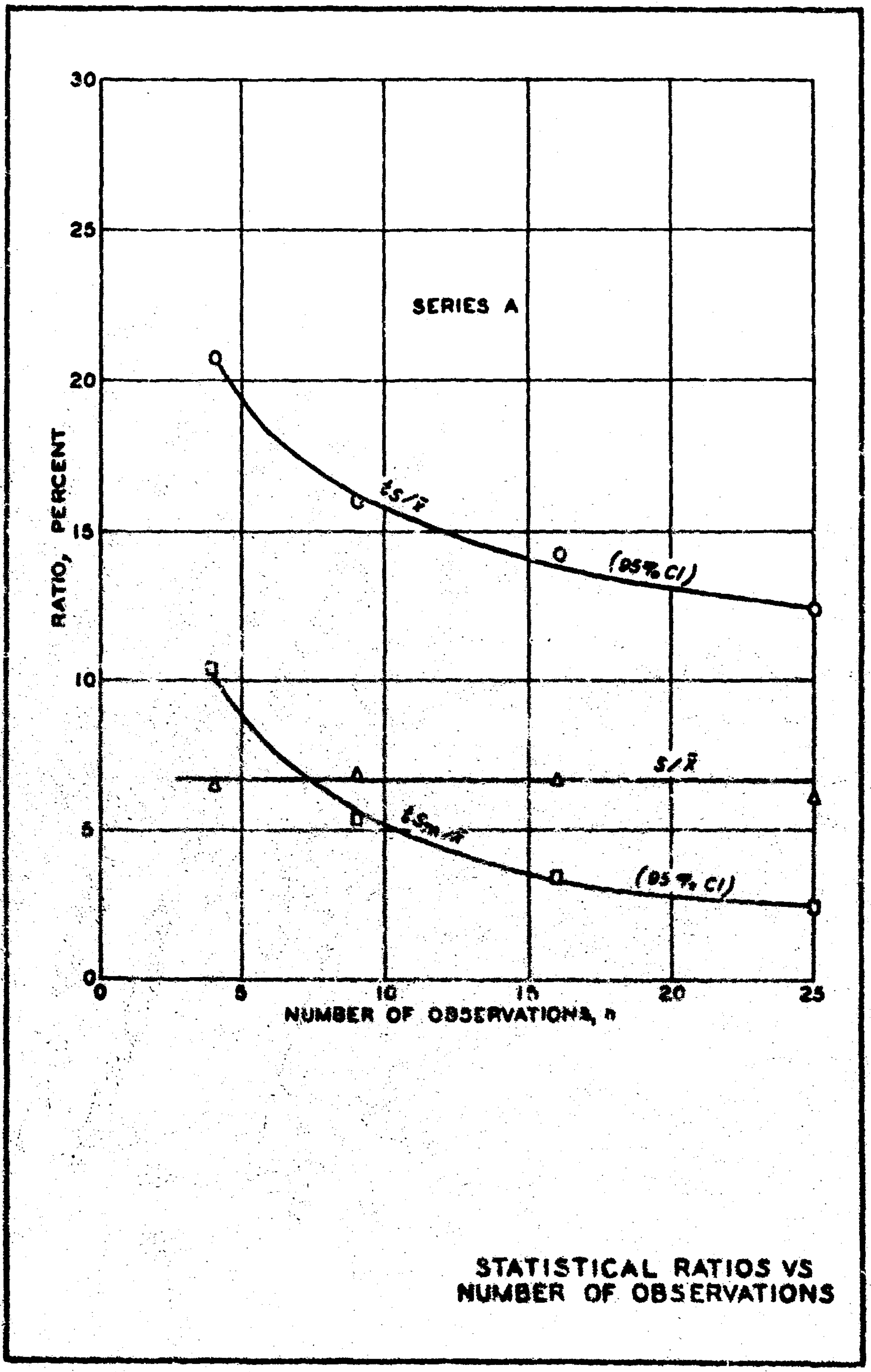
0- TO 6-IN. CPR, PSI
NOTE: EACH POINT REPRESENTS ONE DENSITY OBSERVATION AND AVG OF 4 PENETRATION TESTS NEAREST THE DENSITY TEST
DRY UNIT WEIGHT - γ_d, LB PER CU FT
0- TO 6-IN. CPR, PSI
NOTE: AVG VALUES AND 95% CI OF MEAN BASED ON 4 DENSITY TESTS AND 25 PENETRATION TESTS
DRY UNIT WEIGHT - γ_d, LB PER CU FT
LEGEND
SYMBOL
DENSITY TEST Gp
PENET SERIES
Δ I A
□ II B
O III C
CPR VS UNIT WEIGHT

FIG. 10



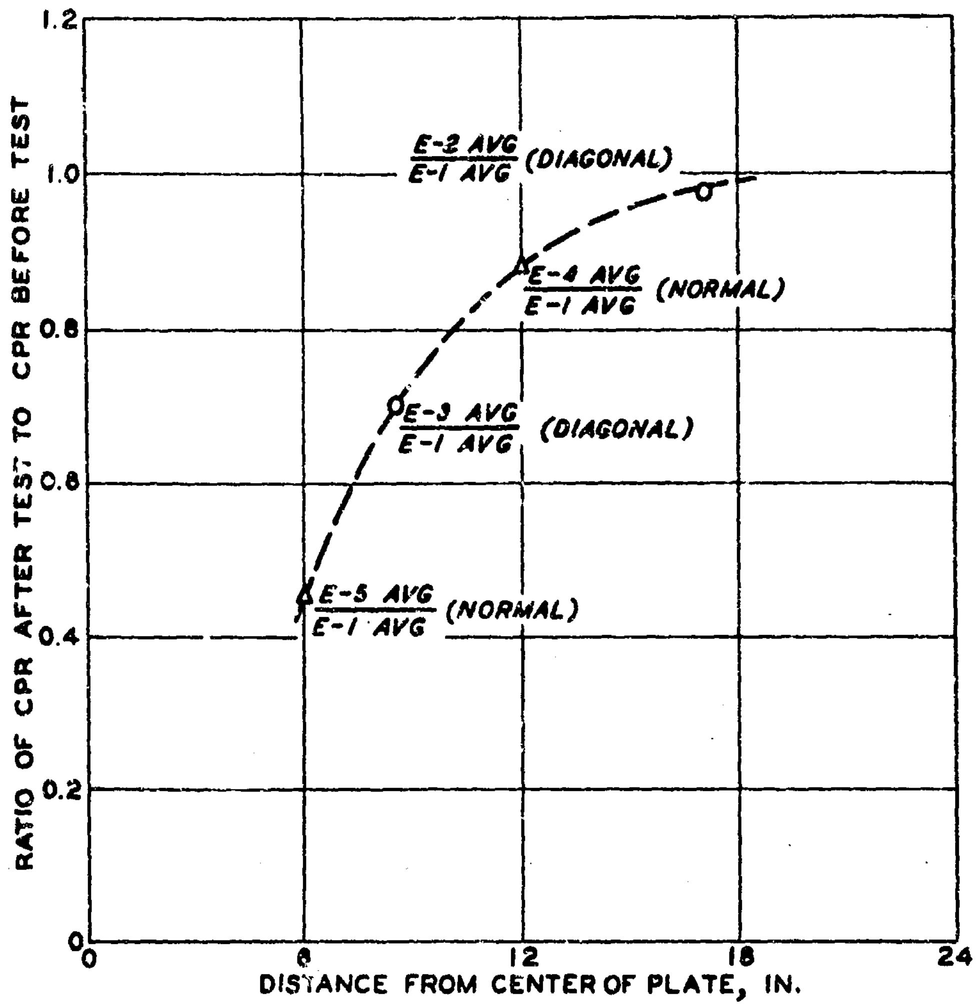
TYPICAL AND IRREGULAR
PENETRATION RESISTANCE
VS DEPTH CURVES

FIG. 11



30
25
20
15
10
5
0
RATIO, PERCENT
SERIES A
$ts/\bar{x}$
(95% CI)
$s/\bar{x}$
$ts_m/\bar{x}$
(95 % CI)
0
5
10
15
20
25
NUMBER OF OBSERVATIONS, n
STATISTICAL RATIOS VS
NUMBER OF OBSERVATIONS

FIG. 17



NOTE: TEST E-1 CONSISTED OF 8 PENETRATIONS MADE BEFORE PLATE-BEARING TEST.

TESTS E-2, E-3, E-4, AND E-5 CONSISTED OF 4 PENETRATIONS EACH MADE AFTER PLATE-BEARING TEST.

EFFECT OF
PLATE PENETRATION
ON CPR

FIG. 1

The 1/4" chemically blown neoprene swim suit was not an adequate insulator, and the stiffness of the material together with its buoyancy completely prevented swimming.

The 1/4" mechanically blown latex swim suit was not tested adequately on account of unavoidable leakage; however, it was determined to be a poorer insulator than the 1/4" ensolyte, and not as flexible.

3. Other observations

Coldness and numbness of the fingers and toes were found to be the major cause of terminating the test, even though the gloves and boots used had the best insulating qualities. Restrictions of circulation at the wrists and ankles by tight gloves and fins quickly caused difficulty. Body temperatures were always of secondary importance to discomfort in the extremities (fingers and toes).

V. CONCLUSIONS AND RECOMMENDATIONS

A. Conclusions

1. The 1/4" flat ensolyte is the best insulator which can be worn readily under the standard swim suit; the 1/4" button ensolyte or other thicker types would be too bulky.

2. The buoyancy of these materials make them unsatisfactory for use as underclothing for swim suits, but would not be a detriment in their use as underclothing for a deep sea diver requiring insulation.

3. The 1/4" flat ensolyte swim suit shows some promise of providing satisfactory insulation for the underwater swimmer, if its depth characteristics are all right.

4. In using any of these materials for cold water swimming or diving, care must be exercised to avoid any restriction in body circulation. Particular attention must be given to the effects of gloves and swim fins at the wrists and ankles.

B. Recommendations

1. Further evaluations should be made, by underwater swimmers, using swim suits of 1/4" flat ensolyte, and other materials presently under development.

2. Evaluation should be made, in the field, by deep sea divers, using various types of ensolyte underclothing.

TABLE I.

Run NO.	Water Temp.	Type of work	Type of Clothing	Duration in minutes	Leakage	Insulating Quality	Swim Buoyancy	Bulk	Remarks
1	36°F	Rest	A	60	1 qt	good	E	E	Circulation restrict- by fins numbed toes
2	36°F	Rest	B	551/2	None	Fair	E	S	Leakage numbed fing- ers, body
3	36°F	Rest	C	61	None	Good	E	E	Circulat. restr. numbed toes
4	36°F	REst	D	20	1 qt	Poor	S	S	Leakage chilled body rapidly
5	36°F	Surface Swim	A	90	None	Good	E	E	Run terminated only by tiring fr.exertion
6	36°F	Surface Swim	D	80	None	Poor	S	S	Run terminated by leak- age, chilling at end.
7	36°F	Surface Swim	B	68	1/2 qt	Fair	E	S	Leakage chilled body
8	36°F	Surface Swim	C	102	None	Good	E	E	Run terminated by out- side conditions
9	36°F	Surface Swim	E	90	1 qt	Good	S	S	Run terminated by out- side conditions
10	36°F	Surface swim	F	23	1/2 qt	Poor	E	E	Subj.chilled, tired fr/ stiff material
11	36°F	Surface swim	G	2	1/2 qt	Poor	E	S	Excessive leakage through material

Types of Clothing

A. 1/4" flat p.v.c. underwear and standard swim suit
B. 1/8" flat p.v.c. underwear and standard swim suit
C. 1/4" button p.v.c. underwear and standard swim suit
D. One suit wool underwear and standard swim suit
E. 1/4" Ensolyte swim suit
F. 1/4" Chemically foamed neoprene swim suit
G. 1/4" Mechanically foamed latex swim suit, outside sprayed with latex.

*E- Excessive
S- Satisfactory